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VCSEL-based DWDM PON with 4 bit/s/Hz Spectral Efficiency using Carrierless Amplitude Phase Modulation

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Abstract: We experimentally demonstrate successful performance of VCSEL-based WDM link supporting advanced 16-level carrierless amplitude/phase modulation up to 1.25 Gbps, over 26 km SSMF with spectral efficiency of 4 bit/s/Hz for application in high capacity PONs.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

The increasing bit-rate per user demand in access networks requires systems that can support higher capacity. In order to satisfy the capacity needs, access networks are moving from classic spectral inefficient non-return to zero time-division multiplexing (NRZ-TDM), to wavelength-division multiplexing (WDM) and more advanced modulation formats. Moreover, the complexity raise has to be kept to the minimum in order make the system feasible for access networks. Different techniques have been used for advanced modulation, such as discrete multi-tone (DMT) [1], and carrierless amplitude/phase CAP [2]. For high-speed transmission, the overall CAP architecture has been demonstrated to be less complex and with better performance than DMT architecture [3]. Moreover, high-speed multilevel CAP implementation has been demonstrated by using analog filters [4].

Vertical cavity surface emitting lasers (VCSELs) are especially attractive for access networks, due to their low manufacturing cost and low power consumption. Compared to edge-emitting lasers, VCSELs have inferior performance in terms of linewidth, chirp, stability or linearity. Therefore it is very important to understand and evaluate the feasibility of employing VCSELs for applications requiring higher laser performance.

Our paper proposes and experimentally demonstrates a VCSEL-based WDM system with CAP modulation for access networks. The experiment successfully demodulates 4 channels 100 GHz spacing after 26 km of SSMF. Each VCSEL is directly modulated at 1.25 Gbps in a 312.5 MHz bandwidth, corresponding to a spectral efficiency of 4 bit/s/Hz. To our knowledge, this is the first demonstration of a VCSEL based WDM CAP system. This shows the potential for using VCSELs as light sources in DWDM PON, supporting spectral efficient modulation formats and operating over a modest baseband bandwidth favoring low complexity electronics.

2. CAP Modulation for Access Networks and short-range links

Carrierless amplitude/phase modulation (CAP) is a multilevel and multidimensional modulation technique proposed by Bell Labs [5]. In contrast with quadrature amplitude modulation (QAM), CAP does not use a sinusoidal carrier to generate two orthogonal components. CAP uses two orthogonal signature waveforms to modulate the data in two dimensions. At the receiver, two filters reconstruct the signal from each component. CAP is especially attractive for access networks and short-range links as it uses low complexity electronics, and more channels allocation due to the high spectral efficiency.

In this experiment, we have used four levels encoding for each dimension generating the so-called CAP-16. Previous publication demonstrated 8 levels encoding CAP-64 [6], 3 orthogonal components 3D-CAP[7] and working with bit-rate up to 40 Gbps [4].

3. Experimental Setup

Figure 1 shows the setup used in the proof of principle experiment. A 500 MHz-bandwidth, 1.25 Gsa/s Arbitrary Waveform Generator (ArbWG) is used to generate the CAP-16 signal at 1.25 Gbps. ArbWG features limits our CAP-16 signal up to 1.25 Gbps with an upsampling 4 to ensure no aliasing products. The 2 outputs of the ArbWG are split in 2 and delayed to emulate 4 x 1.25 Gbps uncorrelated CAP signals. Each uncorrelated CAP signal directly modulates a 1550 nm VCSEL. The output power of each VCSEL is approximately -1 dBm. At the transmitter side, the four wavelengths or channels, are multiplexed with a passive optical power combiner; while at the receiver side, wavelength demultiplexing is done with an arrayed waveguide grating (AWG). The power combiner has conversion loss of 7.5 dB. The AWG has an insertion loss of 1.5 dB. The VCSELs are wavelength-tuned by tuning the bias current in order to fit the 100 GHz-spacing grid of the AWG. Optionally, 2 AWGs with the same grid can be used for multiplexing and demultiplexing wavelengths, resulting in 6 dB additional power margin. The system was

evaluated after 26 km transmission of standard single mode fiber (SSMF), with total fiber attenuation of 7.8 dB. A variable optical attenuator is placed after the fiber for bit error rate (BER) measurements. Each channel is detected by a PIN photodiode and stored in a digital storage scope (DSO) for offline demodulation. The demodulation is done in Matlab by filtering the signal with 2 receiving CAP filters to reconstruct each orthogonal component.

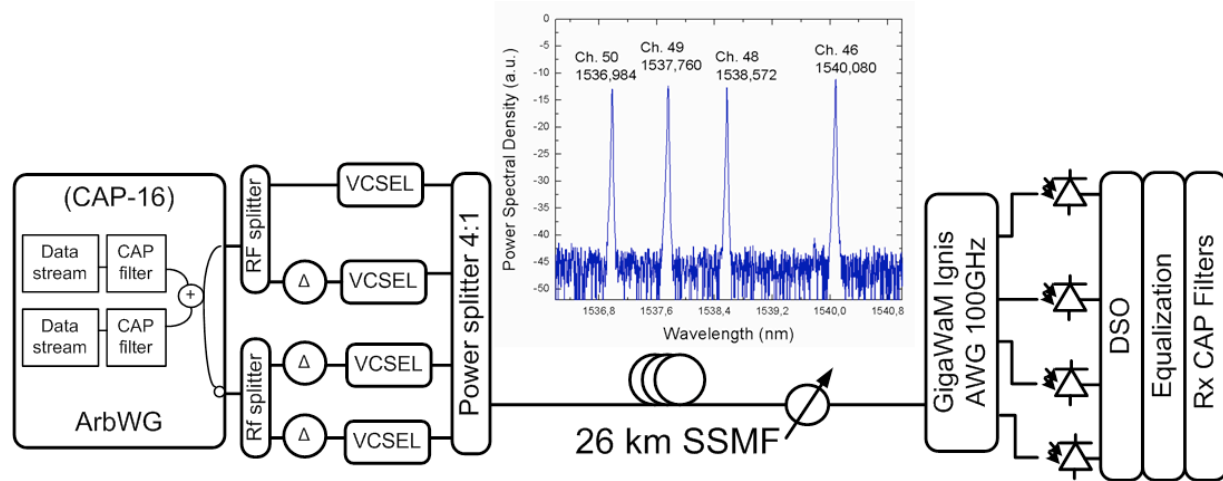


Fig. 1. Experimental Setup. Arbitrary waveform generator (ArbWG), array waveguide grating (AWG), digital storage scope (DSO).

4. Results

The VCSELs were tuned to fit the ITU channels number 50, 49, 48, and 46. The embedded graph in Fig.1 shows the optical spectrum of the WDM-CAP signal with the corresponding wavelengths of each channel.

Figure 2 shows the CAP filters in time and frequency domain, and the electrical spectrum of the CAP signal directly from the ArbWG. The 3dB-bandwidth of each 1.25 Gbps CAP-16 is 312.5 MHz that corresponds to 4 bit/s/Hz spectral efficiency.

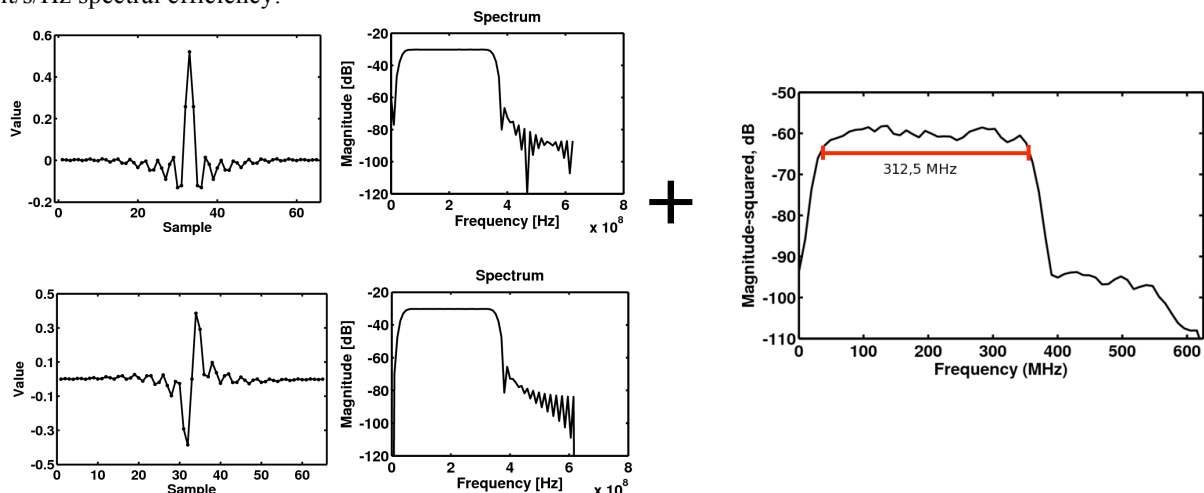


Fig. 2. CAP filters in time and frequency domain, and frequency spectrum of 1.25 Gbps CAP-16 after ArbWG

The received signal filtered with the receiver CAP filters is decomposed in both orthogonal components. Both components can be represented in an I/Q constellation diagram like QAM signals. Fig. 3.a shows the clear constellation diagram of the demodulated electrical B2B signal. Fig. 3.b shows the demodulated optical B2B with -19 dBm received optical power; constellation after electrical-to-optical conversion is still very clear. Fig. 3.c and d show the signals at -22 dBm received optical power, for B2B and after 26 km configurations, respectively. No constellation degradation is appreciated after transmission compared to B2B, as it is shown also later in the BER curves.

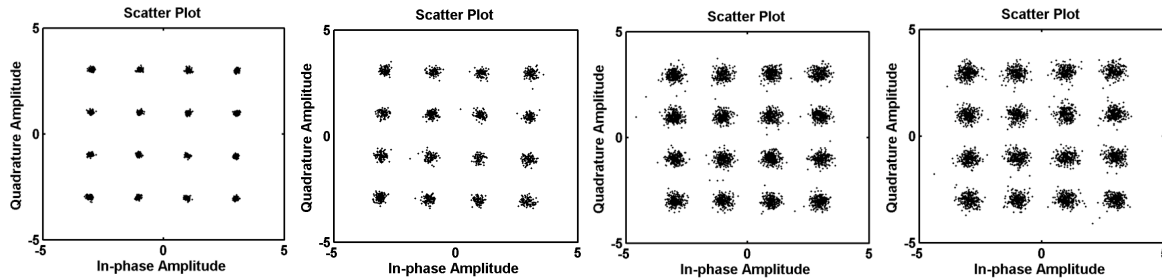


Fig. 3. Constellation CAP-16 for a) electrical B2B, b) optical B2B at -19 dBm, c) optical B2B at -22 dBm, d) after 26 km SSMF at -22 dBm.

Figure 4.a shows the BER curves of the demodulated channel 49 to evaluate the transmission effects and cross talk between channels. The figure compares the performance when only channel 49 is transmitting and when the 4 channels are transmitting simultaneously. No receiver sensitivity power penalty is measured from multiplexing or transmission. Figure 4.b shows all 4 channels after 26 km transmission. The forward error correction (FEC) limit of $\text{BER} = 2.2 \cdot 10^{-3}$ is considered as a reference. We achieved received power sensitivity below -24 dBm for all the channels.

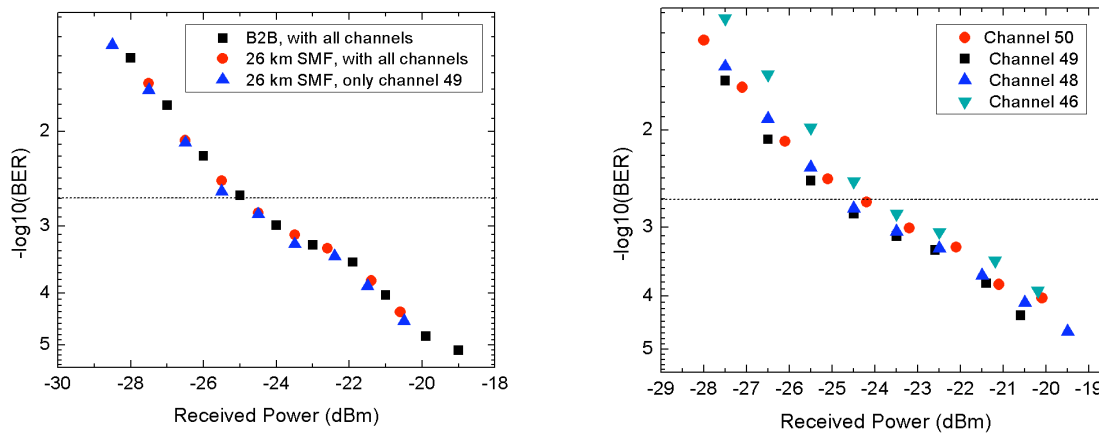


Fig. 4. BER curves CAP-16. a) Channel 49 b) all channels after 26 km SSMF.

5. Summary

We have experimentally demonstrated directly modulation of CAP-16 in commercially available VCSELs, with a spectral efficiency of 4 bit/s/Hz. The system has been evaluated with 4 close spaced channels at 1.25 Gbps each, for a total bitrate of 5 Gbps over 26 km fiber transmission. All the channels achieved received power sensitivity below -24 dBm. Future work will evaluate the system for higher bitrates overcoming the transmitter limitations by using analog CAP filters.

We believe direct CAP modulation of VCSELs is a candidate for next generation PONs and short range systems due to the high spectral efficiency, scalability to higher order modulation, potentially low cost implementation and simplicity compare to modulation formats with carrier.

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